REPORT No. 445

WORKING CHARTS FOR THE DETERMINATION OF THE LIFT DISTRIBUTION BETWEEN BIPLANE WINGS

By Paul Kuhn

SUMMARY

In this report are presented empirical working charts from which the distribution of lift between wings; viz, the fraction of the total lift borne by each, can be determined in the positive lift range for any ordinary biplane cellule whose individual wings have the same profile. The variables taken directly into account include airfoil section, stagger, gap/chord ratio, decalage, chord ratio, and overhang. It is shown that the influence of unequal sweepback and unequal dihedral in upper and lower wings may be properly provided for by utilizing the concepts of average stagger and average gap/chord ratio, respectively. The effect of other variables is discussed, but they have not been included in the charts either because their influence was obviously small or because insufficient data existed to make possible a complete determination of their influence. All available pertinent biplane data were analyzed in establishing the charts, and in some cases theoretical relationships were utilized to establish qualitative tendencies.

INTRODUCTION

The importance of the knowledge of lift distribution is too well known to require much comment. If the structural design of airplanes is to be improved by using methods of stress analysis more refined than those now in use, the applied loads must be known to a higher degree of accuracy.

The determination of the lift distribution between biplane wings is only one phase of the problem of applied loads that has not been satisfactorily solved. The reason lies largely in the absence of a satisfactory biplane theory and in the absence of sufficiently extensive coordinated test data. For instance, the method of determining the lift distribution between biplane wings now recommended by the Department of Commerce (reference 1), is based exclusively on tests of the R. A. F. 15 airfoil, whereas there is considerable evidence that the lift distribution changes with the airfoil section. Furthermore, the recommended rules for determining the effect of overhang and unequal chords are based on inadequate assumptions. Rules in use by the Army and Navy at the time of writing are even more sketchy and incomplete than those in use by the Department of Commerce.

For the above reasons, an analysis of all available biplane test data has been made at the request of the Aeronautics Branch, Department of Commerce, with a view toward further refinement of the method for determining the lift distribution between biplane wings. The present report gives the results of the analysis.

The results are summarized and condensed into working charts from which the lift distribution may be obtained in the positive lift range for any ordinary biplane whose upper and lower wings have the same airfoil section. If C_{L_u}, C_{L_l}, and C_{L_b} denote the lift coefficients, respectively, for the upper wing, lower wing, and their biplane combination, each coefficient can be determined from the other two. In this report the lift distribution is arbitrarily characterized by the ratio $C_{L_u}/C_{L_b} \equiv R$, and is given as a function of the following variables: Stagger, gap/chord ratio, decalage, chord ratio, overhang, and airfoil section. Other variables, such as tip shape, aspect ratio, dihedral, fuselage interference, and scale effect were neglected either because their influence was obviously small or because insufficient data were available to take them properly into account.

METHOD OF PROCEDURE

The procedure followed in arriving at the working charts involved: (1) An examination of available test data bearing on the problem, in which certain of the data were selected as a basis; (2) a comparison of the selected test data with biplane theories; (3) a selection of the most important variables to be included in the charts; and (4) construction of the charts, which were finally based largely on the test data, although certain qualitative relationships were established by the theory.

Test data.—A complete list of references to the test data used in the analysis is given at the end of the report. The test data consist of results from pressure-distribution and force measurements. It was found, where comparable results were available, that the pressure-distribution data were only slightly inferior in accuracy to the force data. Both kinds of data were therefore used.

Comparison of test data from different sources showing the effect of a given variable indicated, in general, a reasonably good agreement. There were, however, three exceptions—the tests reported in references 2, 3, and 4. Reference 2 presents the results of tests on biplanes composed of R. A. F. 6c airfoils. Because the R. A. F. 6c airfoil is now obsolete and because these tests were made before the technic of wind-tunnel testing was well advanced, reference 2 was discarded.

Reference 3 presents the results of extensive tests with the R. A. F. 19 airfoil. This airfoil, although only moderately thick, has an excessive camber and is known to be subject to large scale effects. For that reason, and also because such abnormal airfoils are not commonly used, the results of reference 3 were given no consideration in the analysis.

The results given in reference 4 show a bad scattering in some respects, and the tests were made in such a manner that it is difficult to compare the results with any others. Reference 4 was therefore not used.

Biplane theories.—Although theories of the biplane are plentiful, only Millikan's theory (reference 5) was used, as it is the most complete. This theory was found to be much superior to the older theories, but it was not found to check the experimental data sufficiently well in all cases to serve as a basis for the quantitative determination of the lift distribution. In view of its complexity, attempts to introduce empirical correction factors were considered inadvisable. The theory was therefore used only in certain cases to establish qualitative trends where insufficient data were available to accomplish that result. When adequate data were at hand, the results of calculation by Millikan's theory were not used.

The variables of the problem.—Although the ultimate object of this analysis was to establish a basis for the determination of the lift distribution between the wings of actual biplanes, an insufficient number of tests in which the influence of such factors as the fuselage and slipstream was present were available to permit such a result. By far the most of the data available were obtained from tests on wind-tunnel models in which the fuselage and propeller were absent. For this reason, the problem was considered from two points of view: First, that of the cellule (which is defined here as the combination of two superposed or approximately superposed wings without fuselage); and second, that of the biplane (which is here defined as the cellule plus appurtenances, such as the fuselage, that make up the complete airplane).

Analysis of the data indicated that the distribution of lift between the wings of a cellule is appreciably affected by the following variables: Decalage, stagger, gap/chord ratio, airfoil section, overhang, and chord ratio. Of minor importance are unequal sweepback and unequal dihedral in upper and lower wings. These factors can be dealt with by using an average stagger and average gap/chord ratio, respectively. The influence of tip shape, equal dihedral in both wings, and equal sweepback in both wings is assumed to be negligible. Aspect ratio is probably of small importance within its usual practical limits, and it has also been assumed to be of negligible importance. In unusual designs involving very small aspect ratios, special consideration may, however, be necessary.

The charts.—The charts include the variables listed in the preceding paragraph as having an appreciable influence on the lift distribution. They are arranged in sequence as follows: First, a basic chart (fig. 19, Appendix) which gives R against C_{L_b} for cellules having gap/chord and chord ratios of 1, no overhang, and no decalage; second, a chart (fig. 20, Appendix) giving correction factors for gap/chord ratios other than 1; third, a chart (fig. 21, Appendix) giving correction factors for decalage other than zero; and fourth, a chart (fig. 22, Appendix) giving correction factors for overhang. These factors are to be multiplied by or added to the basic curves to correct for gap/chord ratio, decalage, and overhang, as discussed in the report and detailed in the Appendix. No chart is given for chord ratios other than 1, but means for taking them into account are indicated. The above arrangement and content of the charts are somewhat arbitrary, but they appeared to be logical after an inspection of the data. A discussion of the derivation of these charts in the light of the test data and Millikan's theory follows.

DISCUSSION OF CELLULE DATA AND DERIVATION OF THE CHARTS

The basic chart.—Figure 1 shows a series of experimental R curves for two sets of cellules with gap/chord ratio of 1 having 0° stagger and 30° stagger with different airfoil sections. Comparison of the curves, particularly for 30° stagger, shows that the lift distribution may be taken as a function of the sum of mean camber and thickness, where the mean camber is the camber of the mean line and is measured from the chord subtending the mean line.

An explanation is necessary regarding the Clark Y points. The R curve derived from the tests of reference 6 was found to be somewhat out of place on the camber-thickness scale. This discrepancy was believed to be due to the fact that the individual airfoils used in the cellule had different monoplane characteristics on account of slight differences in the ordinates of the two airfoils. (See reference 5.) Millikan's theory was therefore used in this case. Its validity for the purpose was first established by comparing the experimental Clark Y results with the theoretical R values that were computed using the monoplane characteristics of the experimental airfoils. A close agreement was found up to a biplane lift coefficient of 0.9. This agreement was considered evidence that the theory was correct in this case. Two R values for the Clark Y were therefore recomputed on the basis of monoplane characteristics obtained on an accurate model in the variable-density tunnel (reference 7), and these values were used to represent the Clark Y cellule with 30° stagger in Figure 1.

Figure 2 shows the experimental points for two airfoils at 0°, 15°, and 30° stagger. The curves shown for 0° and 30° are taken directly from the basic chart. The curves for 15° were obtained from the basic chart by straight-line interpolation between the curves for 0° and 30°, i. e., by halving the difference in ordinates; it is therefore apparent that straight-line interpolation for stagger is sufficiently accurate. This conclusion is supported by other test data.

The same figure shows a number of points obtained by using the present design rules. (Reference 1.) They show the errors that are due to basing rules on R. A. F. 15 tests only.

It will be seen in Figure 1 that at 0° stagger the value of R does not appear to be a clearly defined function of the sum of camber and thickness as in the case of 30° stagger. However, the total variation in R for different airfoils at 0° stagger is considerably smaller than at 30° stagger, so that errors involved by assuming that R is still a function of this sum are hardly larger than the experimental errors.

At negative stagger there are very few data (references 6 and 8) other than R. A. F. 15 data in existence. They indicate that at low and medium biplane lift coefficients a single curve adequately represents the tests, and that the difference in airfoil section makes itself felt only near the stalling point.

The basic chart was therefore drawn up (see Appendix, fig. 19), giving the lift-distribution curves for equal span, equal chord cellules with gap/chord ratio of 1 and without decalage as functions of the sum of camber and thickness for staggers of −30°, 0°, and 30°. The chart is based on test results given in reference 6 and references 8 to 16, inclusive.

The gap/chord factor chart.—In Figure 3 three sets of R curves are shown for airfoils at differenct gap/chord ratios. They suggest the possibility of obtaining the R curves for gap/chord ratios other than 1 by multiplying tne R curves of the basic chart by correction factors that depend on the biplane lift coefficient and on the stagger. On the basis of all applicable test data (references 6, 8, and 14), correction-factor curves were derived for a gap/chord ratio of 0.75. These curves are shown in Figure 20. (See Appendix.) It was found that for a stagger of 30° straight lines served the purpose. For 0° it was found necessary to replace the straight lines at lower lift coefficients by curves.

On account of lack of data the factors for −30° stagger were obtained by symmetrical inversion from the factors for 30°. There is no theoretical justification for this procedure, but the resulting factors are well confirmed by test data for the R. A. F. 15 airfoil at two gap/chord ratios. The only applicable test data available for a thick airfoil (fig. 4) do not show more than a fair agreement with the derived factors, but there is not sufficient information available to attempt refinement of the procedure.

For gap/chord ratios between 1 and 0.75 the gap/chord factors may be obtained by straight-line interpolation. A word of caution is necessary here regarding extrapolation of the gap/chord factor chart. The Göttingen 133 airfoil, with a camber-thickness sum of 12.85 at a gap/chord ratio of 0.67 and 37° stagger, which represents extrapolation both for stagger and gap/chord ratio, shows fair agreement (fig. 8, decalage = 0°), but the Clark Y with a camber-thickness sum of 15.4 at a gap/chord ratio of 0.5 shows a large discrepancy at 0° stagger (not illustrated). Consequently, extrapolation to gap/chord ratios below approximately 0.65 is hazardous, particularly for airfoils with a camber-thickness sum of 13.0 or more.

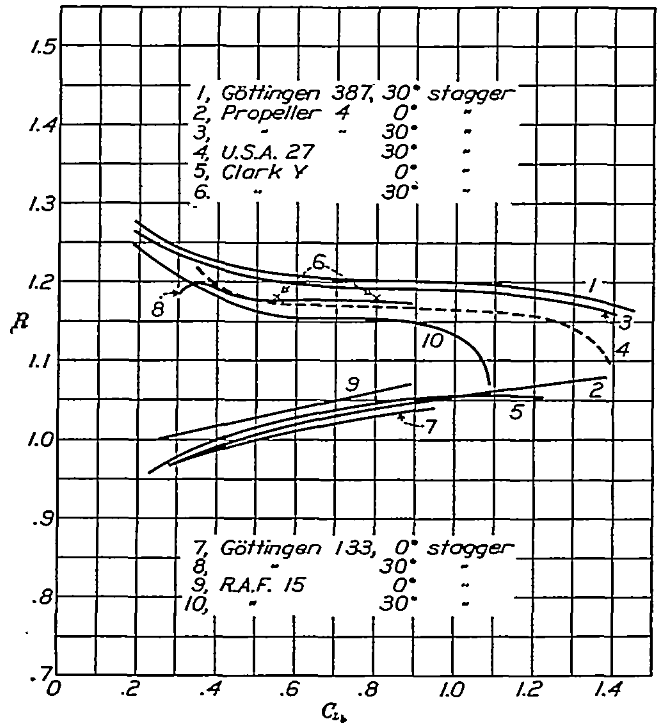
If it be assumed that for a gap/chord ratio of 3 the biplane interference has disappeared, then $R=1$ for this gap/chord ratio and larger ones. This result may be used to obtain R curves for gap/chord ratios larger than 1 by interpolating lineally between the R curve for a gap/chord ratio of 1 (and for the given stagger) and between the R curve for the gap/chord ratio of 3, which is $R=1$ regardless of stagger. The R curves obtained by this method of interpolation agree reasonably well with the test data.

Figure 4 shows experimental points and R curves derived from the charts for the U. S. A. T. S. 5 at 0°, 30°, and −30° stagger and at a gap/chord ratio of 0.9. Figure 5 similarly compares the experimental points and R curves from the charts for the Clark Y at three values of stagger and at a gap/chord ratio of 0.75. The relatively large disagreement at 33⅓° stagger may be attributed, in part, to the differences between the upper and lower wings of the Clark Y cellule mentioned in the discussion of the basic chart.

The decalage-factor chart.—Figures 6, 7, and 8 show the results of some tests on cellules with varying amounts of decalage. From these and similar tests (reference 6, 9, and 14), decalage-factor curves have been derived (see Appendix, fig. 21) in a manner similar to that by which the gap/chord factor curves were obtained. The decalage-factor curves are not, however, straight lines. The decalage factors are seen to depend on the gap/chord ratio and the stagger, but not on the airfoil section. No test results are available at negative stagger, so no curves could be given for this case.

In Figure 8 the discrepancy between the experimental points and the R curves determined by using the charts is larger than in the cases shown in Figures 6 and 7. Examination of the figure shows, however, that the discrepancies are systematic and are due to the fact that the basic curve for 0° decalage is too high at low and medium lift coefficients. It should be pointed out, too, that the basic curve for this case was extrapolated from the charts both for stagger and gap/chord ratio.

When dealing with the influence of gap/chord ratio it was assumed that R is always 1 for a gap/chord ratio of 3. If there is no biplane interference, R depends on the ratio of the angles of attack of upper wing and cellule (average of upper and lower) and on the slope of the monoplane lift curve. Assuming for the latter an average value of 0.075, it was possible to draw the decalage-factor curve for a gap/chord ratio of 3 (any stagger) which can be used to obtain factors for gap/chord ratios larger than 1 by straight-line interpolation. This relation is expressed by curve 5, Figure 21.

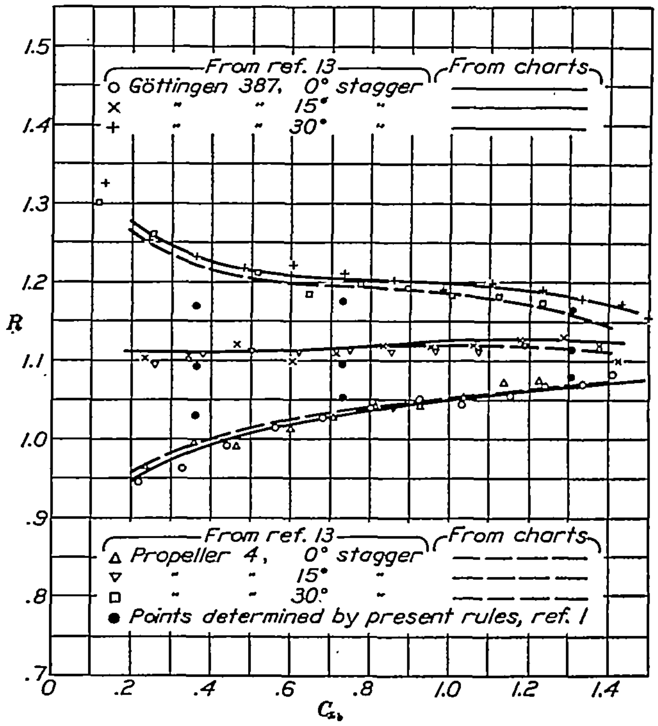


Airfoil	Göttingen 387	Propeller 4	U. S. A. 27	Clark Y	Göttingen 133	R. A. F. 15
Maximum mean camber, per cent chord	5.9	5.7	5.4	3.8	4.6	2.6
Maximum thickness, per cent chord	15.1	12.7	11.0	11.7	8.1	6.4
Gap/chord ratio	1.0	1.0	1.0	1.0	1.0	1.0
Chord ratio	1.0	1.0	1.0	1.0	1.0	1.0
Decalage, degree	0	0	0	0	0	0
Percentage overhang	0	0	0	0	0	0
Reference	13	13	13	5, 6	14	8, 10, 11, 12

FIGURE 1.—Experimental lift-distribution curves for biplane cellules

The overhang-factor chart.—Comparison of the experimental curves for the Clark Y with varying overhang (fig. 9) shows that except possibly for very low lift coefficients, the effect of overhang is to shift the R curve vertically by amounts proportional to the percentage of overhang, where percentage of overhang is defined as $\frac{\text{upper span}-\text{lower span}}{\text{upper span}}\times 100$. At first glance this does not seem to hold for negative overhang at low lift coefficients. There is, however, a possibility that an error of ¾° decalage may have existed in the test set-up which would account for the apparent discrepancy between the results at positive and negative overhang. For this reason it was assumed that in all cases the change in R is proportional to the amount of overhang. Figure 22 (see Appendix) shows the derived overhang factors.

It will be noticed that Figure 22 requires the overhang factor to be multiplied by the chord ratio. This rule is based on the consideration that the effect of overhang is due chiefly to a change in aspect ratio of one of the wings. If one wing has a smaller chord and consequently a larger aspect ratio, the effect caused by



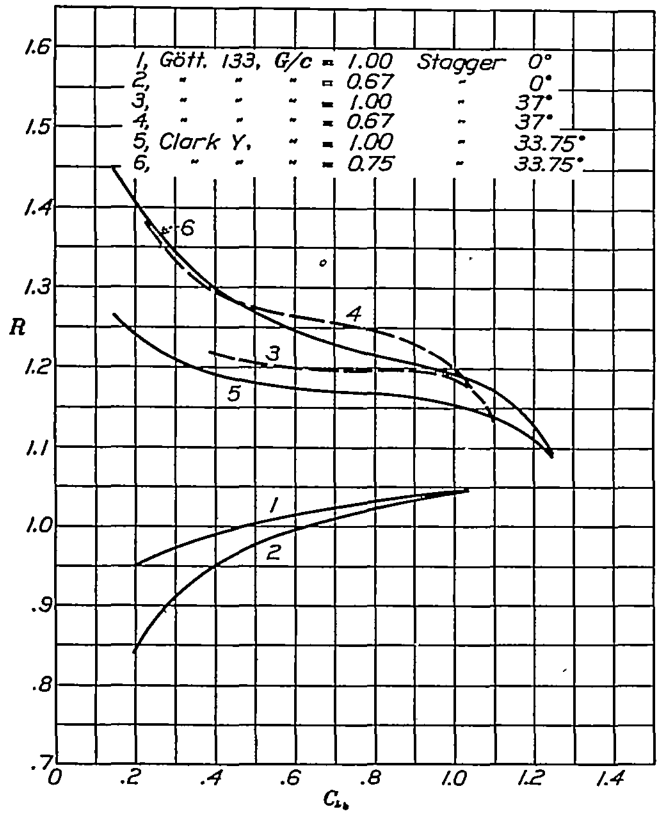
Airfoil	Göttingen 387	Propeller 4
Maximum mean camber, per cent chord	5.9	5.7
Maximum thickness per cent chord	15.1	12.7
Gap/chord ratio	1.0	1.0
Chord ratio	1.0	1.0
Decalage, degree	0	0
Percentage overhang	0	0
Reference	13	13

FIGURE 2.—Lift distribution in cellules with Göttingen 387 and Propeller 4 airfoils

changing its aspect ratio will be less. The variation of the overhang factor with stagger is based on simple aerodynamical considerations and is at least partly substantiated by test data. (Fig. 10.)

The influence of chord ratio.—If an equal-chord cellule be compared with a cellule having the lower chord smaller than the upper (assuming the upper wing to be the same in both cases), a qualitative consideration of the changes indicates that the ratio R in the unequal-chord cellule will be nearer 1 than in the equal-chord cellule. The same effect is produced by increasing the gap/chord ratio of the equal-chord cellule. It seems possible, therefore, to treat the unequal-chord case by introducing an effective gap/chord ratio.

At the same time, however, the question of stagger must be considered. The stagger has been measured in the past at the leading edges, the quarter-chord points, the one-third chord points, and the half chord points. Some of these points were chosen merely for convenience, others with some aerodynamical reasoning. Examination of the curves from references 17 and 18 (fig. 10) suggested that the stagger should be measured at points even farther back. The three-quarter chord points were chosen as convenient reference points. When this was done and when an effective gap/chord



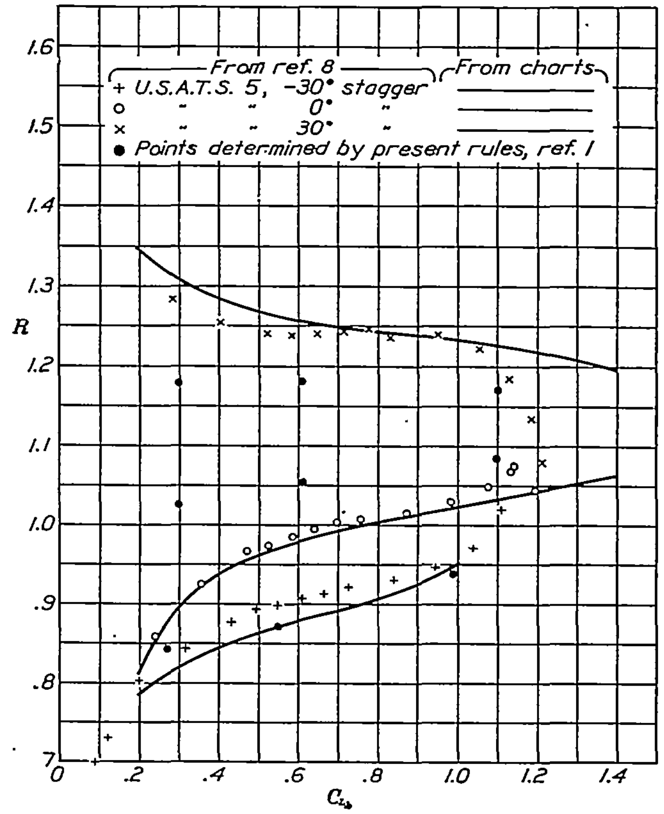
Airfoil	Göttingen 133	Clark Y
Maximum mean camber, per cent chord	4.6	3.8
Maximum thickness, per cent chord	8.1	11.7
Chord ratio	1.0	1.0
Decalage, degree	0	0
Percentage overhang	0	0
Reference	14	6

FIGURE 3.—Change in lift-distribution curves due to change in gap/chord ratio

ratio based on the actual gap and the lower chord was used, the charts were found to check the few test results available. (Fig. 10 and fig. 11, decalage = 0°, taken from references 17, 18, 19, and 20.)

In the absence of test data at larger staggers, basic curves were calculated by the Millikan theory; from these R curves were obtained for certain unequal-chord biplanes with a chord ratio of 2 by interpolation. These curves are shown in Figure 12. The same unequal-chord biplanes were then computed directly, also by means of Millikan's theory; the results are shown by the symbols on the figure and are seen to check the curves quite well.

The same procedure was followed with biplanes having a chord ratio of 1:2 inasmuch as there were no test data available for cellules in which the lower wing had the larger chord. The results, also shown in Figure 12, are seen to check well at negative stagger, but not quite so well at large positive stagger. Because the degree of accuracy of the theory is uncertain, these calculations can serve only as weak evidence, but they tend to strengthen the conviction that the proposed method of measuring an effective stagger and an effec-



Airfoil	U. S. A. T. S. 5
Maximum mean camber, per cent chord	5.4
Maximum thickness, per cent chord	17.5
Gap/chord ratio	.9
Chord ratio	1.0
Decalage, degree	0
Percentage overhang	0
Reference	8

FIGURE 4.—Comparison of experimental points with curves from charts for U. S. A. T. S. 5 airfoil

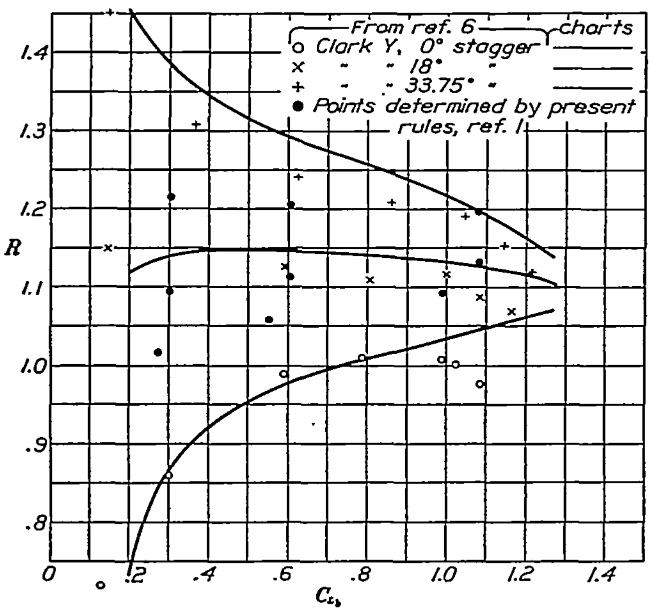
tive gap/chord ratio gives a fair approximation for the lift distribution.

Minor factors.—As has been stated before, the influence of equal dihedral and sweepback on both wings can probably by entirely neglected. For the case of unequal dihedral, the lift distribution can be obtained, with small error, by assuming no dihedral and measuring the gap at a section including the centroid of the semicellule. For practical purposes, any convenient section may be used for measuring the gap, since the differences in the lift distribution with slight changes in gap are very small at normal gap/chord ratios.

Unequal sweepback can be taken into account by measuring the stagger at the centroid of the semicellule. Experimental evidence of the validity of this procedure is shown in Figure 13.

The influence of tip shape is probably negligible, as indicated by the fact that almost all the data were consistent even though they represent airfoils with square tips, semicircular tips, and raked tips.

The influence of increasing the aspect ratio above 6 up to the practical limit probably has not much influence on the lift distribution. One test at aspect ratio 5.6 (reference 21) shows no variation from the others, but it is probable that for aspect ratios below this there will be a rapidly increasing influence. However, such cases are rare.



Airfoil	Clark Y
Maximum mean camber, per cent chord	3.8
Maximum thickness, per cent chord	11.7
Gap/chord ratio	.75
Chord ratio	1.0
Decalage, degree	0
Percentage overhang	0
Reference	6

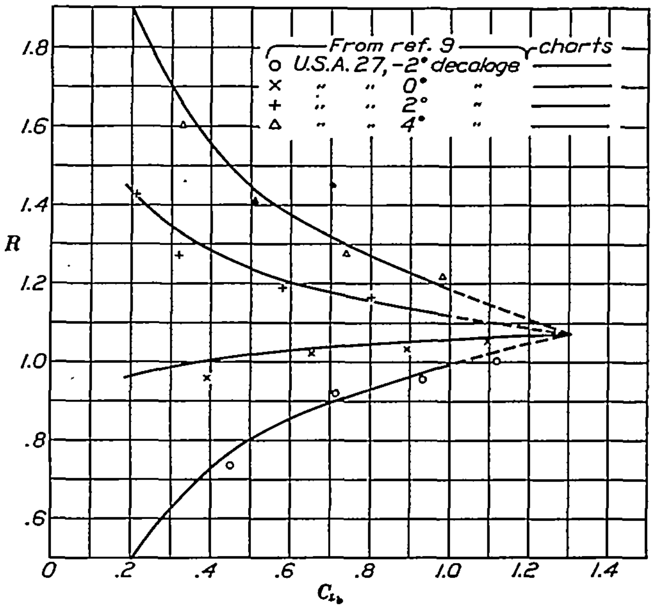
FIGURE 5.—Comparison of experimental points with curves from chart for Clark Y airfoil

PRECISION OF THE CHARTS

It must be borne in mind that the charts are based on tests of airfoils having a flat lower surface or only a moderate degree of lower camber. They should therefore be used only for such airfoils. As a matter of interest, curves are shown for a widely different type of airfoil. (Fig. 14.)

Between $C_{L_b}=0.3$ and approximately 90 to 95 per cent $C_{L_{max}}$ the deviation of experimental points from the R curves of the working charts is generally less than 0.03 except in cases involving decalage. Below $C_{L_b}=0.3$ the error increases rapidly and at $C_{L_b}=0.2$ is in a number of cases about 0.10. At $C_{L_b}=0.2$, however, an error in decalage of 0.2° in the test set-up will cause an error in R of about 0.05. Since 0.2° was about the limit of accuracy of the decalage setting in most of the wind-tunnel tests forming the basis of this analysis and since decalage is not the only source of error, discrepancies of 0.10 between the R curves and experimental data at $C_{L_b}=0.2$ are not surprising. Below $C_{L_b}=0.2$ the test results scatter so badly that the curves were discontinued at this point.

As the burbling point depends on the Reynolds Number and other factors besides the airfoil, the R curves are unreliable near this point. They should not be relied on above 90 per cent $C_{L_{max}}$ where $C_{L_{max}}$ is taken, if possible, from wind-tunnel tests on a comparable biplane combination. If such tests are unavailable, the termination of the curves may be used as a rough indication of the burbling point. The U. S. A. T. S. 5 burbled considerably sooner than the chart would indicate (fig. 4), but for most tests the curves gave a good approximation practically up to the experimental burbling point.



Airfoil	U. S. A. 27
Maximum mean camber, per cent chord	5.4
Maximum thickness, per cent chord	11.0
Gap/chord ratio	1.0
Chord ratio	1.0
Stagger, degree	0
Percentage overhang	0
Reference	9

FIGURE 6.—Effect of decalage on U. S. A. 27 airfoil

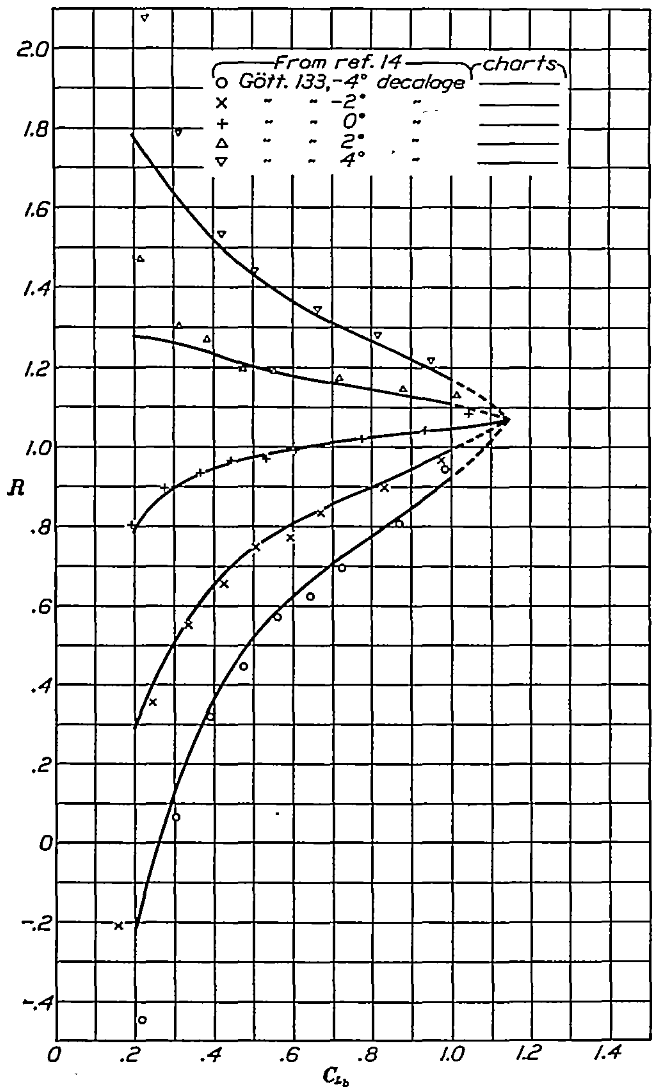
The accuracy of curves obtained by means of the decalage factors is somewhat lower than the general accuracy of the curves involving no decalage. The maximum deviation of experimental points may be taken as about 0.05 for decalage up to 6° and between $C_{L_b}=0.3$ and 0.95 $C_{L_{max}}$.

APPLICATION OF THE CHARTS TO COMPLETE BIPLANES

The model biplane.—Aerodynamic investigators have realized that it is important to test not only component parts of the airplane, but also the complete assembly, since interference effects may be very large. Numerous tests of this type have been made for other purposes, but only a single test is available where the complete model with fuselage was tested to obtain the loads on the upper and the lower wing separately.

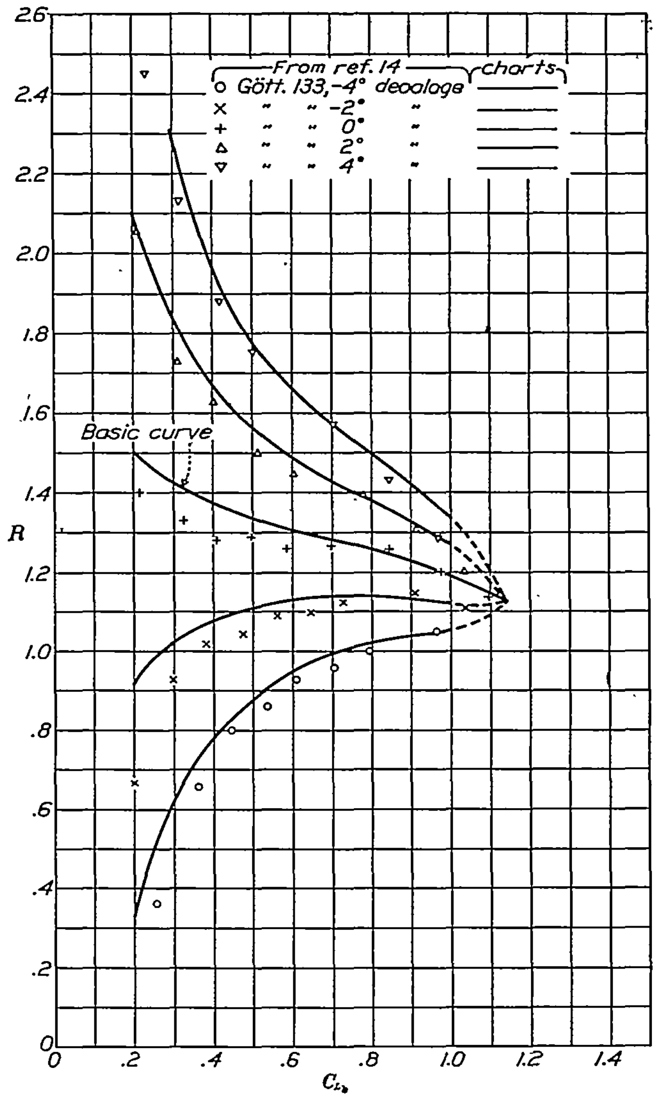
This test, reported in reference 22, shows a very considerable influence of the fuselage. (Fig. 15.) The value of R is approximately 14 per cent higher than predicted from the chart. The span-load curves for the lower wing in this case show a very marked falling off toward the center line of the airplane. This effect is probably somewhat larger than would ordinarily be expected because a rather large opening existed between the root of the wing and the fuselage.

Tests on the influence of a fuselage on the wings of a low-wing monoplane (reference 23) have shown that even without such a gap at the root of the wing, a very marked reduction of the lift may occur. Figure 16, which was derived from data given in reference 23, shows the curve of lift coefficient against angle of attack for different types of fuselages attached to the wing; for unfavorable fuselage shapes as much as 20 per cent of the lift may be lost due to interference from the fuselage. It should be noted, too, that the



Airfoil	Göttingen 133
Maximum mean camber, per cent chord	4.6
Maximum thickness, per cent chord	8.1
Gap/chord ratio	.67
Chord ratio	1.0
Stagger, degree	0
Percentage overhang	0
Reference	14

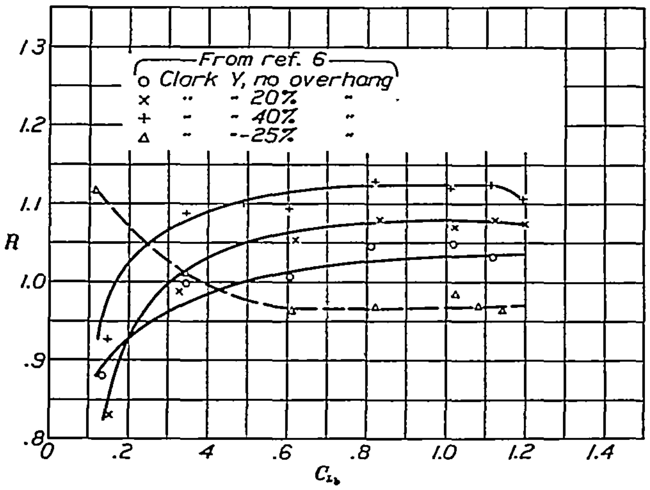
FIGURE 7.—Effect of decalage on Göttingen 133 airfoil



Airfoil	Göttingen 133
Maximum mean camber, per cent chord	4.6
Maximum thickness, per cent chord	8.1
Gap/chord ratio	.67
Chord ratio	1.0
Stagger, degrees	37
Percentage overhang	0
Reference	14

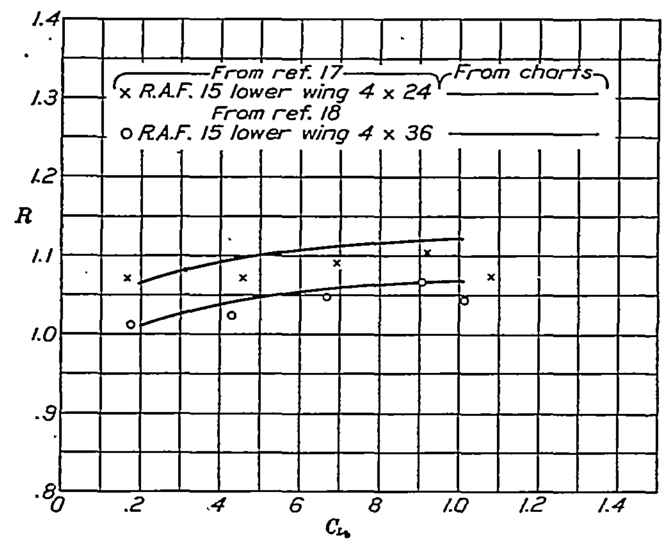
FIGURE 8.—Effect of decalage on Göttingen 133 airfoil

lift used is the total lift of the combination, whereas the reference area is the wing area; consequently, the decrease in lift coefficient on the wing itself is even larger than indicated on the figure. Such an effect



Airfoil	Clark Y
Maximum mean camber, per cent chord	3.8
Maximum thickness, per cent chord	11.7
Gap/chord ratio	1.0
Chord ratio	1.0
Stagger, degree	0
Decalage, degree	0
Reference	6

FIGURE 9.—Experimental lift distribution on cellule with overhang



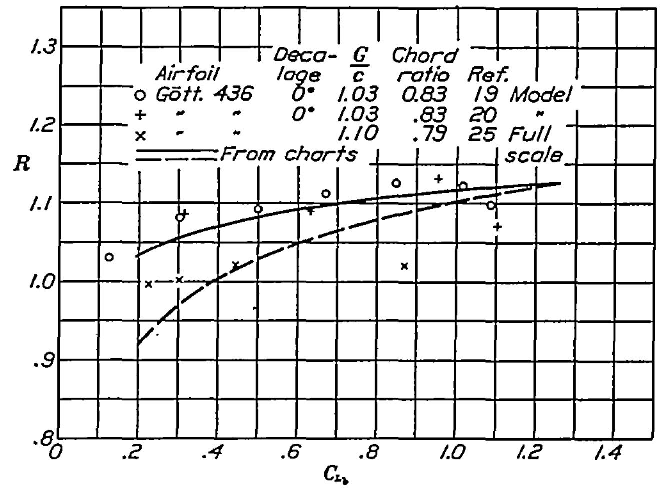
Airfoil	R. A. F. 15	R. A. F. 15
Upper wing	6 by 36	6 by 36
Lower ring	4 by 36	4 by 24
Gap, inches	4.5	4.5
Stagger, degrees at L. E.	20	20
Decalage, degree	0	0
Reference	18	17

FIGURE 10.—Lift distribution for unequal-chord biplanes with and without overhang

might be considered to be comparable to conditions on the lower wing of a biplane. An opposite effect may be expected on the upper wing.

The influence of the fuselage will be extremely difficult to predict, because it depends so much on the fairing of the wing root into the fuselage, the size and shape of windshields, the gap between the fuselage and upper wing, and other factors. The lack of tests on complete biplane models is to be very much deplored.

The full-scale biplane.—The oldest complete pressure-distribution tests were made on the MB-3 pursuit airplane. (Reference 24.) This airplane has a very unusual feature in that the upper wing has a washout of 3°, while the lower wing has a washin of 1°. In the computation of the *R* curve for this airplane it was assumed that it would be sufficiently accurate to use the average incidence for each wing, resulting in a decalage of 2°. However, it is evident that this assumption can give only a rough approximation, particularly at low angles of attack. Figure 17 shows



Airfoil	Göttingen 436	Göttingen 436
Maximum mean camber, per cent chord	3.9	3.9
Maximum thickness, per cent chord	11.2	11.2
Gap/chord ratio	1.1	1.03
Chord ratio	.79	.83
Stagger (approximate)	0	0
Percentage overhang	29.75	29.75
Reference	25	19, 20

FIGURE 11.—Lift distribution on PW-9 airplane

a comparison of the experimental points with the *R* curve. The agreement at high lift coefficients is fair, particularly considering the fact that the pressure-distribution measurements are made with only a very few orifices per rib. The agreement at low lift coefficients is very much poorer, as was expected. The dotted lines show the lift distribution at the maximum load during pull-ups from dives. As no time histories were given, the biplane lift coefficient at which these maximum loads occurred could not be computed.

A more comprehensive and more detailed series of measurements was made on the *PW-9*. (Reference 25.) It is mentioned in this reference that the airplane had an accident that caused, later on, frequent changes in rigging, of which no continuous record was kept. The deviations of the experimental points from the *R* curve at high and intermediate speeds could be explained by ½° of decalage. (Fig. 11.) This possibility is made plausible by a close examination of the photograph of the airplane that shows that the right upper wing, on which the measurements were made, had less incidence than the left upper wing. However, the true explanation of the discrepancy is probably to be found largely in the differences in lift distribution due to the slipstream.

Figure 18 shows a series of points obtained from the time histories of mild pull-ups with power off. It will be seen that these points group much more closely around the R curve, the influence of the slipstream

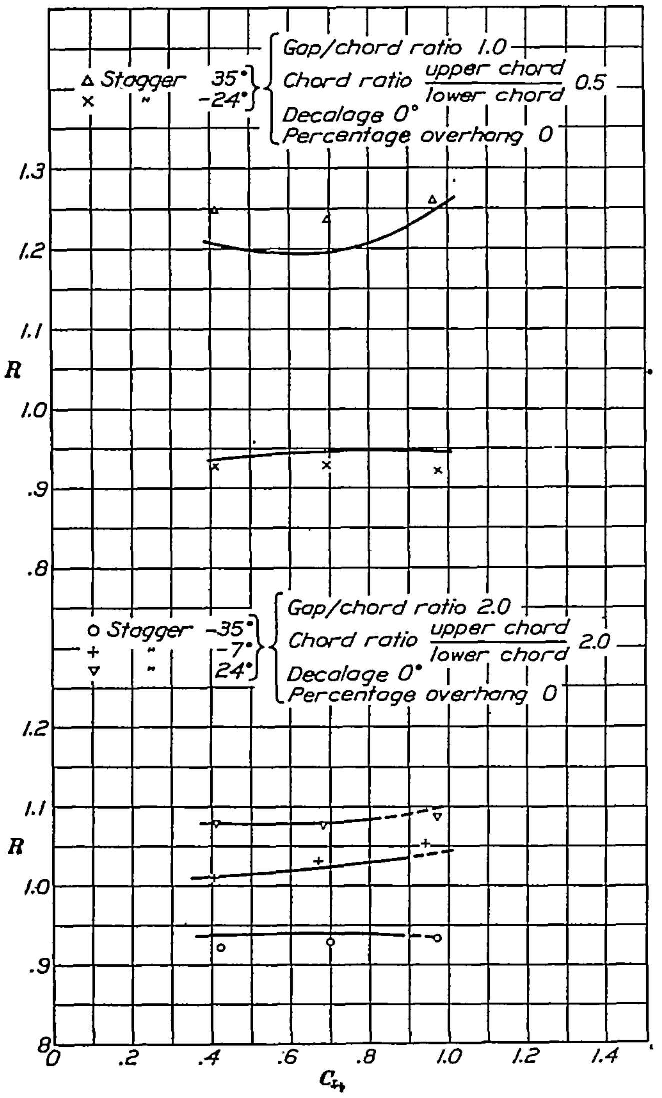
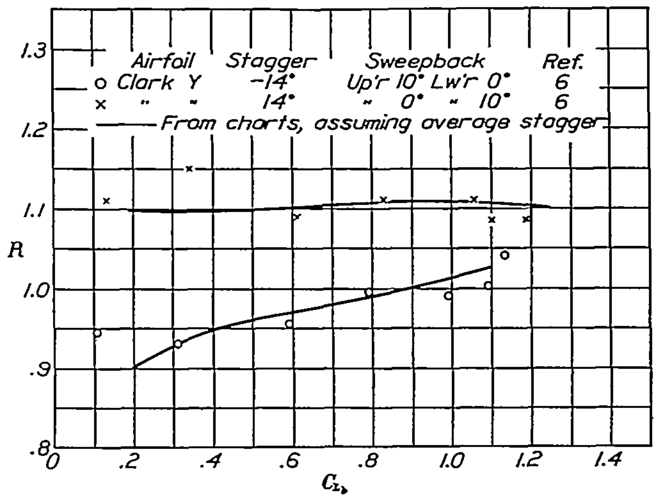


FIGURE 12.—Lift distribution for unequal-chord biplanes by Millikan's theory

being smaller in this case. Another peculiarity, however, appears on this chart; that is, a number of points are beyond the range of biplane lift coefficients which are obtained in steady flight or in the wind tunnel. This phenomenon, which is more pronounced in abrupt pull-ups, is discussed in reference 25, where it is pointed out that the increased maximum lift coefficient occurs mainly on the upper wing and is probably caused by the high rate of change of angle of attack. Recently, wind-tunnel tests have been made in Germany (reference 26) in which the angle of attack was increased suddenly by changing the direction of the air stream. A formula is given for the increase in lift coefficient as a function of chord, speed, and rate of change of angle of attack. The formula, applied to the PW–9 tests, gives maximum values for the increase in maximum lift coefficient which are, in general, only about half as great as the observed values. The higher coefficients obtained in the PW–9 pull-ups, however, might be expected as a result of the fact that the Reynolds Number in the pull-ups was more than twice as great as that in level flight.

More attention should be given this subject in future research to determine how the critical loads depend on the maximum lift coefficient of the pitching wing.

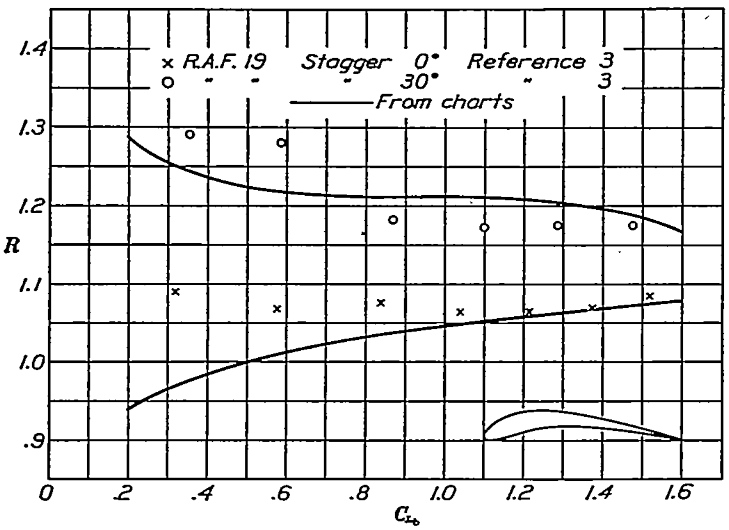


Airfoil	Clark Y
Maximum mean camber, per cent of chord	3.8
Maximum thickness, per cent of chord	11.7
Gap/chord ratio	1.0
Chord ratio	1.0
Decalage, degree	0
Percentage overhang	0

FIGURE 13.—Validity of average stagger assumption for unequal sweepback in upper and lower wings

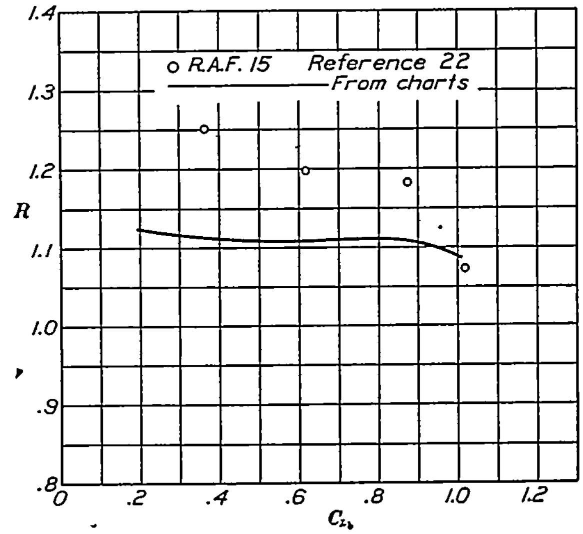
RECOMMENDATIONS

As far as our knowledge of the cellule is concerned, tests are desirable on the following doubtful points: (1) Effect of unequal chords; (2) effect of unequal chords in combination with overhang and decalage (unequal-chord tests should include cellules with the upper wing having the smaller chord); (3) effect of gap/chord ratio below 1, using airfoils of different thicknesses and cambers. In one otherwise excellent series of tests an attempt was made to evaluate this effect by making only one test at a gap/chord ratio of 0.5, which is probably below any practical dimension. The argument was that such a test would show in an exaggerated way the influence of low gap/chord ratios. This argument seems unsound, for, at such low gap/chord ratios, so many other factors begin to exert an influence that it is difficult to draw any general conclusions from such an experiment.



Airfoil	R. A. F. 19
Maximum mean camber, per cent of chord	10.52
Maximum thickness, per cent of chord	9.9
Gap/chord ratio	1.0
Chord ratio	1.0
Decalage, degree	0
Percentage overhang	0
Reference	3

FIGURE 14.—Lift distribution on a cellule with R. A. F. 19 airfoil



Airfoil	R. A. F. 15
Maximum mean camber, per cent of chord	2.6
Maximum thickness, per cent of chord	6.4
Gap/chord ratio	.985
Chord ratio	1.00
Stagger	17° 20′
Decalage	0°
Percentage overhang	0
Reference	22

FIGURE 15.—Lift distribution on a B. E. 20 airplane model

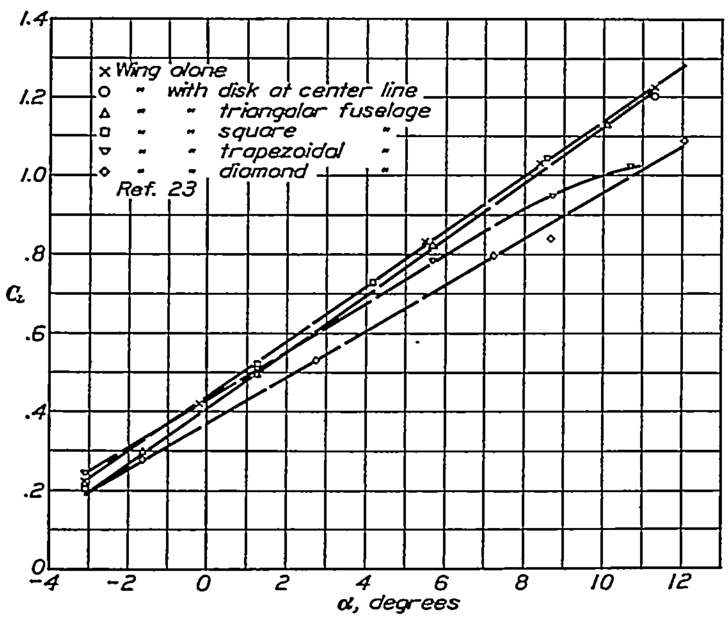
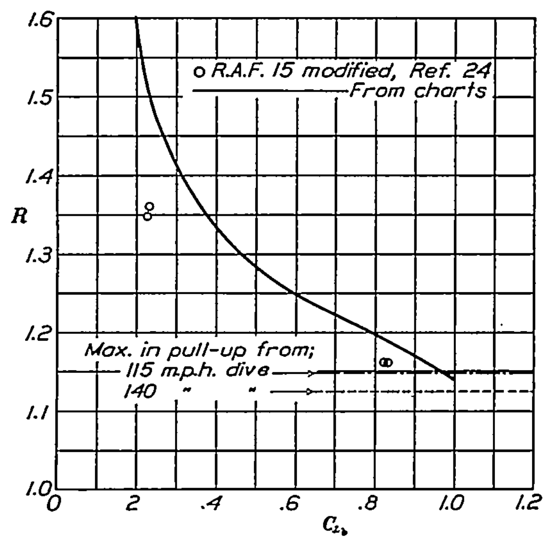
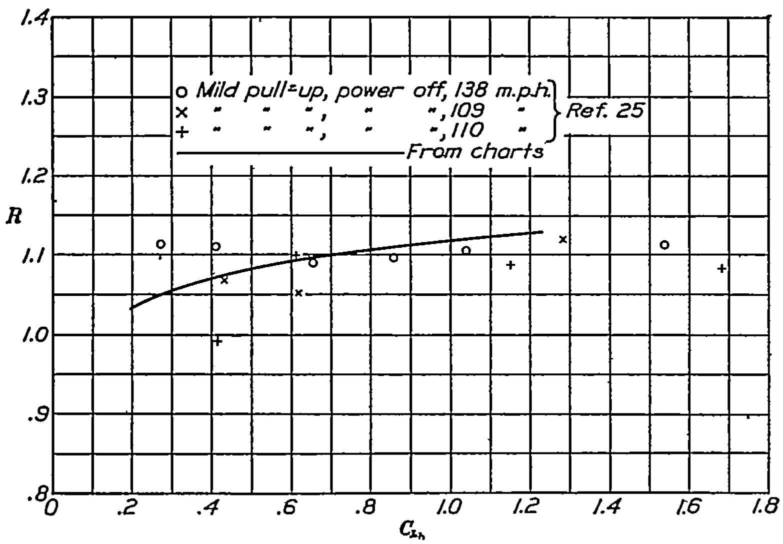


FIGURE 16.—Influence of fuselage shape on lift of low-wing monoplane



Airfoil	R. A. F. 15 (modified)
Maximum mean camber, per cent of chord	2.6
Maximum thickness, per cent of chord	6.4
Gap/chord ratio	.86
Chord ratio	1.0
Stagger, degree	0
Decalage, degrees	2
Percentage overhang	5.8
Reference	24

FIGURE 17.—Lift distribution on MB-3 airplane



Airfoil	Göttingen 436
Maximum mean camber, per cent of chord	3.9
Maximum thickness, per cent of chord	11.2
Gap/chord ratio	1.1
Chord ratio	.79
Stagger, degree (approximate)	0
Decalage	------
Percentage overhang	29.75
Reference	25

FIGURE 18.—Comparison of predicted and experimental lift distribution on the PW-9 airplane

No information at all is available on the important subject of biplane lift distribution in inverted flight. Some tests should be made at negative lift up to the maximum negative lift coefficient.

Design rules should take into account possible variations in decalage caused by errors or arbitrary changes in rigging. In view of the fact that lack of data prevented the establishment of correction factors for decalage at negative stagger, the decalage correction for 0° stagger may be applied to allow for rigging changes in biplanes having negative stagger until test data become available.

The influence of interferences, particularly that caused by the fuselage, should be studied more extensively. The effects of fuselage interference should be recognized in formulating design rules for the load distribution between biplane wings. Such effects might be tentatively included in the allowance for accidental positive decalage.

LANGLEY MEMORIAL AERONAUTICAL LABORATORY,
NATIONAL ADVISORY COMMITTEE FOR AERONAUTICS,
LANGLEY FIELD, VA., *July 11, 1932.*

APPENDIX

USE OF THE CHARTS

The fundamental idea of the charts is, briefly, that one chart gives the lift-distribution, or R, curve for the basic biplane; that is, the equal-span, equal-chord biplane without decalage, and with a gap/chord ratio of 1. The other charts give correction factors that are multiplied by or added to the basic curves to take account of decalage, overhang, and gap/chord ratios other than 1.

The important characteristics of the biplane are listed below in the sequence in which they appear in the determination of the R curve:

(1) Airfoil section.
(2) Gap/chord ratio.
(3) Chord ratio.
(4) Stagger.
(5) Decalage.
(6) Overhang.

(1) The airfoil is taken into account by selecting the proper curve for the sum of camber and thickness. This applies to the basic chart (fig. 19) and to the gap/chord factor chart (fig. 20).

(2) The gap/chord ratio is taken into account:

(*a*) For gap/chord ratios less than 1, by multiplying corresponding ordinates of the basic R curve and of the proper gap/chord factor curve. (Fig. 20.) The method of interpolating to find the proper gap/chord factor curve is explained under the subhead Interpolation of Factors.

(*b*) For gap/chord ratios greater than 1, by interpolating lineally between the R curve for the gap/chord ratio of 1 and the R curve for the gap/chord ratio of 3, which is $R=1$.

(*c*) The gap/chord factors are used only for the staggers for which they are given; viz, 30°, 0°, and −30°. If the biplane has any other stagger, say 17°, it is necessary to find the R curves for 0° and 30° stagger at the given gap/chord ratio and to interpolate between these two R curves to obtain the R curve for 17° stagger.

(3) If the chord ratio differs from 1, an effective gap/chord ratio, which is the actual gap divided by the chord of the lower wing, is used.

(4) The stagger used is an effective stagger measured in degrees between the line connecting the three-quarter chord points and a perpendicular to the chord of the upper wing in a plane containing the centroid of the semicellule. This method of measuring stagger must be borne in mind in the case of unequal-chord biplanes.

The R curve for a stagger other than 30°, 0°, or −30° is obtained by straight-line interpolation. For 17°, for instance, the R curves are drawn for 0° and 30° and the curve for 17° is found by linear interpolation between them.

The end points of the 0° and −30° curves are connected by a straight line to determine the end points of curves for negative stagger; otherwise the procedure is the same as for positive stagger.

(5) Decalage is provided for by multiplying corresponding ordinates of the basic curve and of the proper decalage-factor curve. (Fig. 21.) The interpolation for finding the proper decalage-factor curve is explained under the subhead Interpolation of Factors. For C_{L_b} greater than 1.0, the end of the R curve is faired into the end of the basic curve as indicated by dotted lines in Figures 6, 7, and 8.

(6) Overhang is provided for by adding to the R curve the overhang correction from Figure 22 after all other corrections have been made.

INTERPOLATION OF FACTORS

(1) **Gap/chord factor.**—The gap/chord factor chart gives the factor curves for a gap/chord ratio of 0.75. From these, the factor curve for a gap/chord ratio between 0.75 and 1 is obtained by linear interpolation, remembering that the factor is 1 for a gap/chord ratio of 1.

(2) **Decalage factors.**—There are two cases—

(*a*) $G/c<1$:

For example let $G/c=0.8$; stagger = 17°.

In Figure 21, between the F_d curve for ($G/c=1.0$, stagger = 0°) and the F_d curve for ($G/c=0.75$, stagger = 0°), interpolate to obtain the F_d curve for ($G/c=0.8$, stagger = 0°).

Between the F_d curve for ($G/c=1.0$, stagger = 30°) and the F_d curve for ($G/c=0.75$, stagger = 30°), interpolate to obtain the F_d curve for ($G/c=0.8$, stagger = 30°).

Between the F_d curve for ($G/c=0.8$, stagger = 0°) and the F_d curve for ($G/c=0.8$, stagger = 30°) interpolate to obtain the F_d curve for ($G/c=0.8$, stagger = 17°).

(*b*) $G/c>1$:

Let $G/c=1.25$; stagger = 17°.

Between the F_d curve for ($G/c=1.0$, stagger = 0°) and the F_d curve for ($G/c=1.0$, stagger = 30°) interpolate to obtain the F_d curve for ($G/c=1.0$, stagger = 17°).

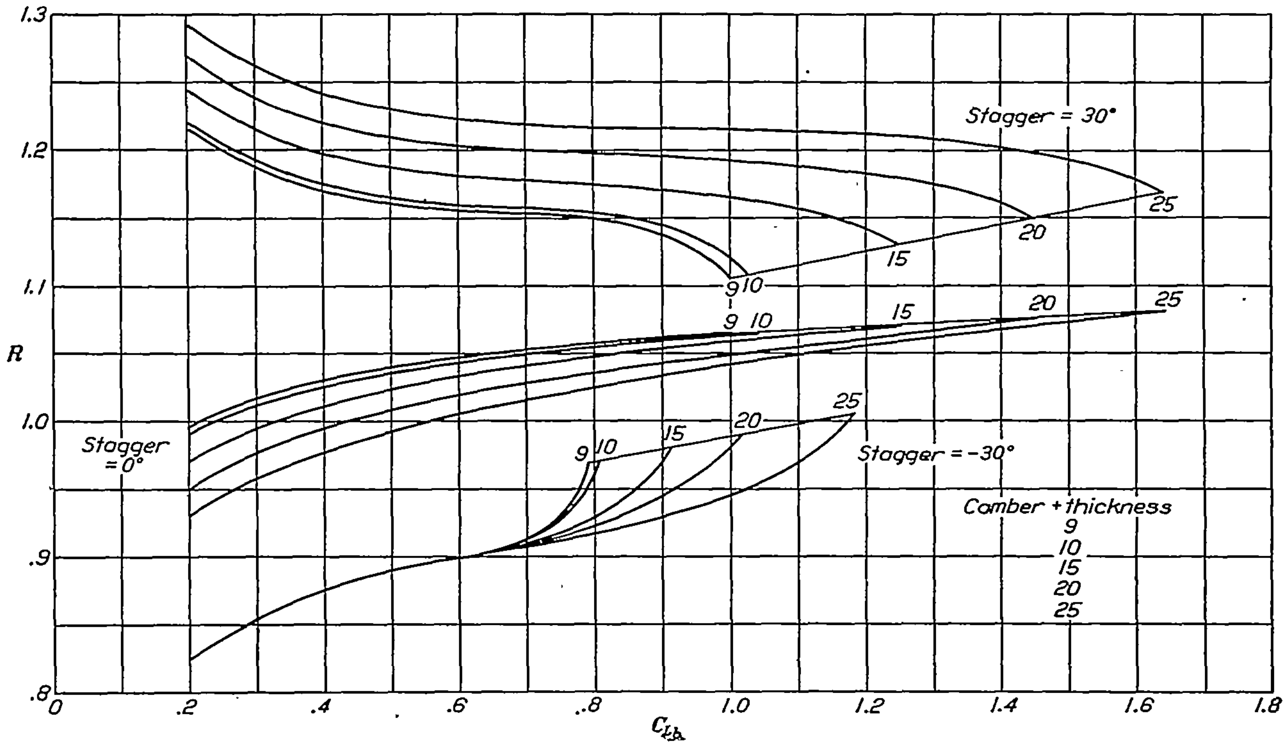


FIGURE 19.—Basic lift-distribution chart for biplanes

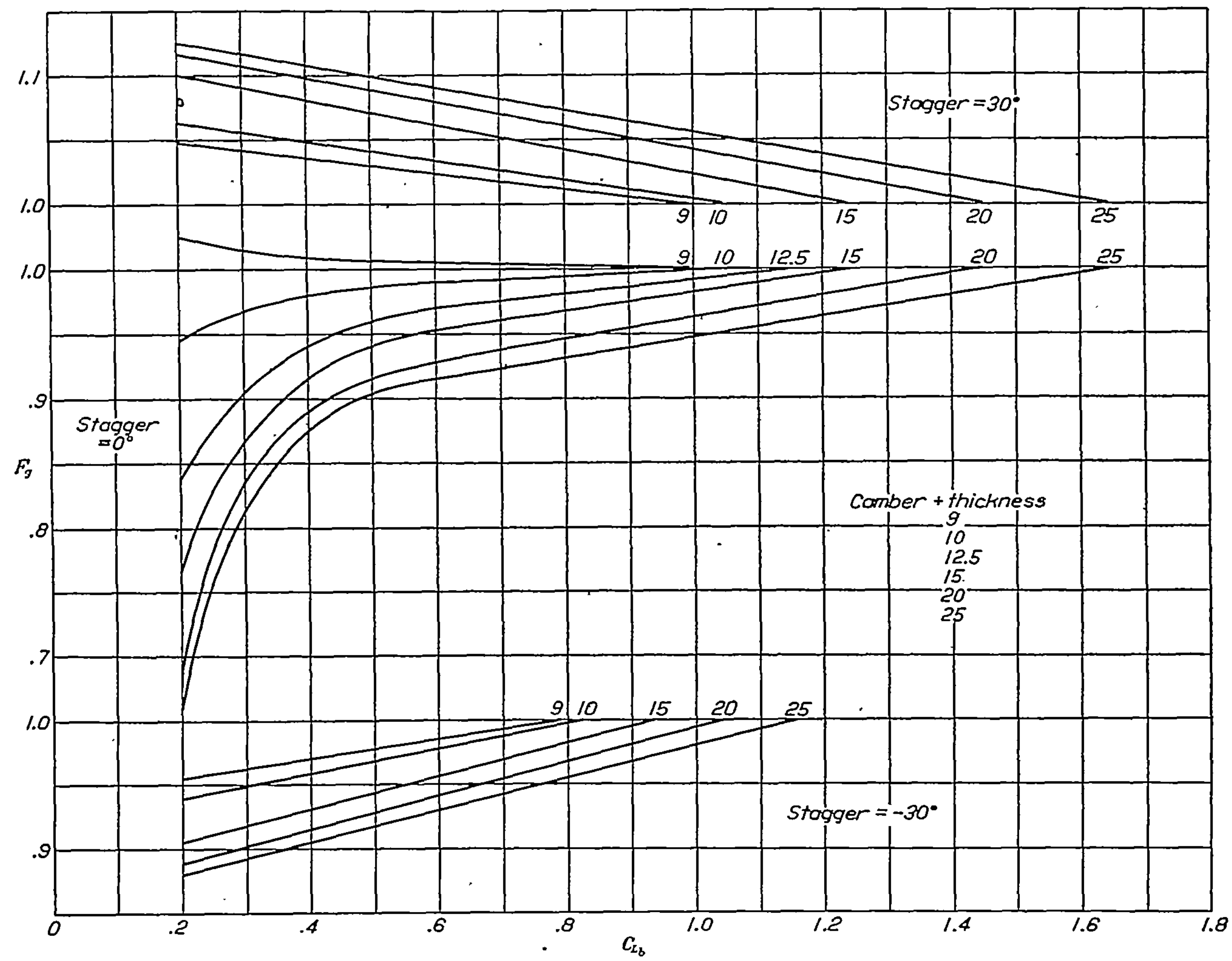


FIGURE 20.—Gap/chord factors. $G/c=0.75$

Between the F_d curve for ($G/c=1.0$, stagger $=17°$) and the F_d curve for ($G/c=3$) interpolate to obtain the F_d curve for ($G/c=1.25$, stagger $=17°$).

Example.—The following is an example of the procedure for finding R against C_{L_b} in the most general case.

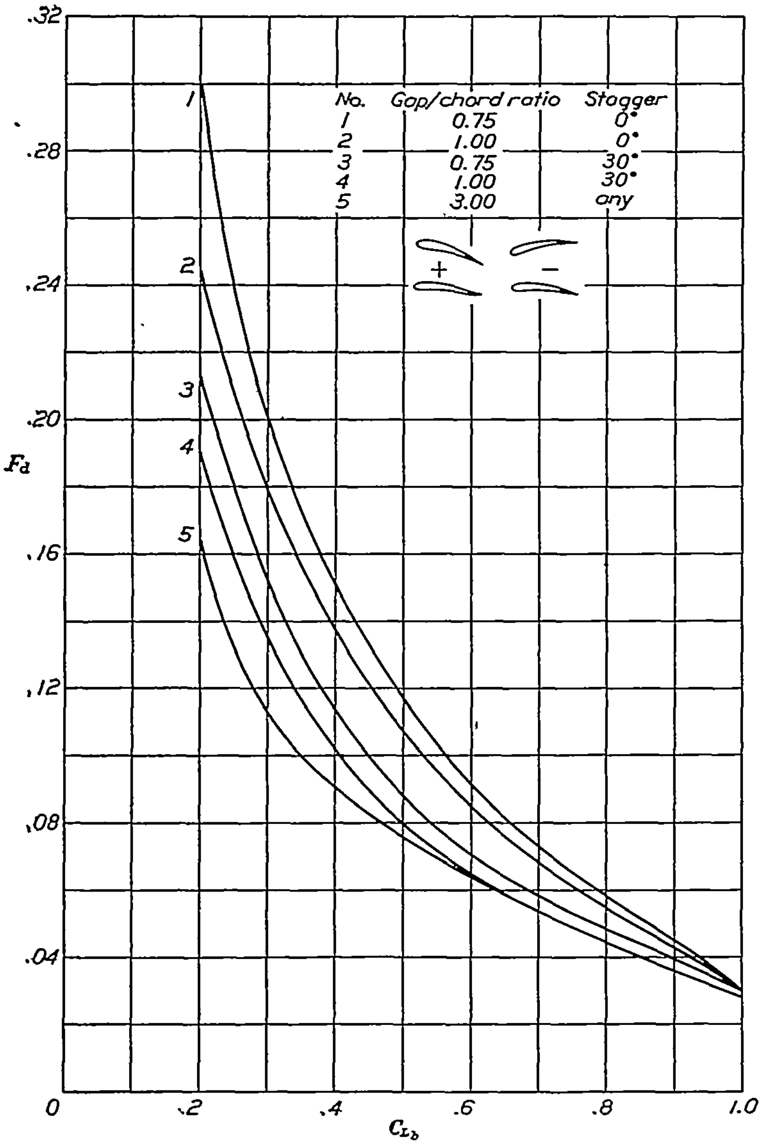


FIGURE 21.—Decalage factors $=(1+d\times F_d)$ F_d from chart. d=decalage in degrees

DATA

Airfoil—Clark Y
Camber + thickness: 15.5.
Span, upper: 40 ft.
Span, lower: 30 ft.
Chord, upper: 7 ft.
Chord, lower: 5 ft.
Gap: 4.5 ft.
Stagger: 13° (measured at the three-quarter chord points).
Decalage: 1.5°.
Gap/chord ratio: 0.9.

The following list explains the significance of each item in Table I and tells how it is obtained.

(1) R values for $G/c=1$, (camber + thickness) $=15.5$, stagger $=30°$ from Figure 19.

(2) R values for stagger $=0°$.

(3) G/c factor for (camber + thickness) $=15.5$, stagger $=30°$, $G/c=0.75$ from Figure 20.

(4) G/c factor for stagger $=30°$, $G/c=0.9$ by interpolation; $(4)=1+[(3)-1]\times\frac{0.1}{0.25}$.

(5) G/c factor for (camber + thickness) $=15.5$, stagger $=0$, $G/c=0.75$ from Figure 20.

(6) G/c factor for (camber + thickness) $=15.5$, stagger $=0$, $G/c=0.90$ by interpolation from (5); $(6)=1-[1-(5)]\times\frac{0.1}{0.25}$.

(7) R values for $G/c=0.9$, stagger $=30°$; $(7)=(1)\times(4)$.

(8) R values for $G/c=0.9$, stagger $=0°$; $(8)=(2)\times(6)$.

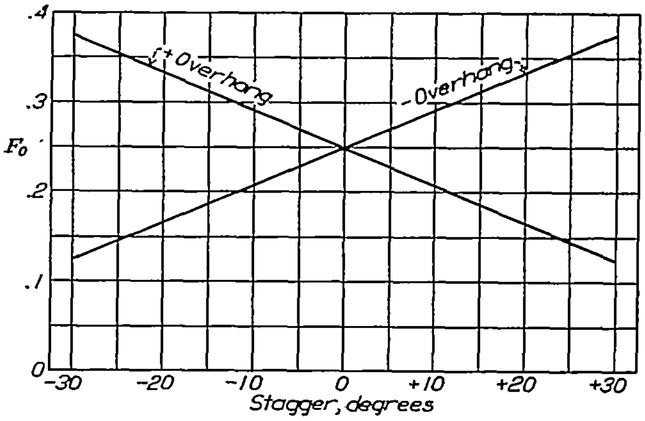


FIGURE 22.—Overhang factors.

Overhang correction $=F_o\times\frac{\text{upper span}-\text{lower span}}{\text{upper span}}\times\frac{\text{smaller chord}}{\text{larger chord}}$

(9) Difference between R values, (7) and (8).

$(10)=(9)\times\frac{13}{30}$ (interpolating for stagger).

(11) R values for $G/c=0.9$, stagger $=13°$; $(11)=(8)+(10)$.

(12) Decalage factors, F_d, for $G/c=0.9$, stagger $=0°$ by interpolating in ratio $\frac{0.1}{0.25}$ between F_d curves for $G/c=1$, stagger $=0°$ and $G/c=0.75$, stagger $=0°$ on Figure 21.

(13) Decalage factors for $G/c=0.9$, stagger $=30°$ obtained in a manner similar to (12).

(14) Difference between (12) and (13).

$(15)=(14)\times\frac{13}{30}$ (interpolating for stagger).

(16) F_d values for $G/c=0.9$, stagger $=13°$; $(16)=(13)+(15)$.

(17) Complete decalage factor for 1.5° decalage; $(17)=1+1.5\times(16)$.

(18) R values for $G/c=0.9$, stagger $=13°$, decalage $=1.5°$; $(18)=(11)\times(17)$.

(19) Overhang correction from Figure 22 $=0.197\times\frac{10}{40}\times\frac{5}{7}=0.035$.

(20) Final R values by adding (19) to (18).

TABLE I.—*Calculation of typical R curve*

C_{L_b}	0.2	0.4	0.6	0.8	1.0	1.26
Item No.:						
(1)	1.247	1.199	1.183	1.177	1.167	1.131
(2)	.968	1.008	1.030	1.044	1.056	1.071
(3)	1.102	1.083	1.063	1.044	1.025	1.000
(4)	1.041	1.033	1.025	1.017	1.010	1.000
(5)	.758	.913	.950	.965	.980	1.000
(6)	.903	.965	.980	.986	.992	1.000
(7)	1.299	1.239	1.213	1.197	1.179	1.131
(8)	.875	.973	1.010	1.029	1.048	1.071
(9)	.424	.266	.203	.168	.131	.060
(10)	.184	.115	.088	.073	.057	.026
(11)	1.059	1.088	1.098	1.102	1.105	1.097
(12)	.266	.142	.086	.057	.029	---------
(13)	.199	.106	.067	.046	.029	---------
(14)	.067	.036	.019	.011	.000	---------
(15)	.029	.016	.008	.005	.000	---------
(16)	.228	.122	.075	.051	.029	---------
(17)	1.342	1.183	1.112	1.076	1.043	1.000
(18)	1.421	1.288	1.221	1.186	1.153	1.097
(19)	$0.197\times\frac{40-30}{40}\times\frac{5}{7}=0.035$					
(20)	1.456	1.323	1.256	1.221	1.188	1.132

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